Challenge: How Effective is Routing for Wireless Networking?

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ABSTRACT

In this paper, we examine the question of how effective routing is for reliably and efficiently delivering data in a wireless network. With the emergence of the Internet of Things, there is a renewed focus on multi-hop wireless networking to connect these systems of smart-devices. Many of the proposals to support this new networking paradigm continue to use the concept of routing: a path between users is formed via a series of point-to-point links. We believe that the characteristics of the wireless environment inherently make link-based routing unsuitable for wireless networking, and that new approaches need to be considered. In this paper, we demonstrate that link-based routing (1) experiences high packet loss due to the inherently unreliable nature of control information, (2) is unable to ensure reliable message delivery in a lossy environment, and (3) incurs a high cost for route maintenance and repair.

1. INTRODUCTION

Despite years of research and development, there are few real-world examples of multi-hop wireless networks. Today, almost all of our wireless devices communicate directly with a base station (such as WiFi or cellular), where these access points are able to maintain high-quality links with their users. But with the advent of the Internet of Things, the number of wireless networked devices is expected to reach into the billions [1–3], To support this emerging network of "smart-objects", there has been a renewed interest in using wireless multi-hop networking to interconnect these devices [4–6]. These devices will often be low-power, and will be expected to operate in a lossy environment [7–9]. While new proposals for wireless networking standards attempt to make them more lightweight [10, 11], more power-efficient [12], and more robust [13], these new proposals still share the same basic operating principle of previously developed networking schemes: control information is disseminated throughout the network to identify a set of links to route data across. This technique for routing in wireless networks is an extension of those initially developed for wired networks. In this paper, we examine the question of whether or not the traditional scheme of link-based routing is effective for reliably and efficiently delivering data in wireless networks.

The basic approach for routing is to create a path between two users that is composed of a series of point-to-point links, where each point on the path is responsible for forwarding data across a link towards the next waypoint. Since routing protocols rely on transmitting data across a series of links, we refer to these schemes as "link-based". Almost all wireless routing protocols (reactive, proactive, link state, distance vector, geographic, etc.) are link-based [14]. Furthermore, newly proposed wireless networking standards continue the approach of link-based routing [12, 15–18].

We hypothesize that the reliance on "links" in wireless routing protocols prevents these schemes from working well in a wireless environment. The idea of a link is borrowed from wired networks. In a wireless network, there is no one-to-one connection between two radios; transmissions are typically overheard by multiple users. Error-prone connections and mobile users prevent next-hop waypoints along a path from acting as reliable data relays. Any link-state information is inherently unreliable, and can quickly become stale. Since wireless channels are frequently changing, constant route maintenance must be performed, with this maintenance incurring a high cost in bandwidth limited wireless networks. There has been work in trying to improve the quality of links selected for routes [19, 20], but as we show, link-based routing remains unreliable even when these improvements are used, especially in a lossy environment.

We believe that the characteristics of the wireless environment inherently make link-based routing unsuitable for wireless networking. Requirements for the future Internet of Things are just beginning to be defined, and while applications in these networks may vary

widely, one thing that is generally agreed upon is that networking schemes to support these future networks must be scalable and provide high reliability [8, 9, 21, 22]. In this paper, we use simulation and analysis to demonstrate that traditional wireless routing protocols will not necessarily be effective at meeting these challenges, and that new approaches may need to be considered. In particular, we demonstrate the following:

1. In an "ideal" wireless environment, link-based routing experiences high packet loss due to the inherently unreliable nature of control information.

2. In a more realistic lossy environment, link-based routing is incapable of reliable message delivery.

3. The route repair and maintenance process that link-based routing schemes employ to overcome link errors is costly, not scalable, and ultimately unable to ensure reliable message delivery.

To demonstrate our results, we examine two popular link-based routing protocols: Ad-Hoc On-Demand Distance Vector (AODV) [23] and Optimized Link State Routing (OLSR) [24]. AODV is used in the ZigBee multi-hop networking standard [25], and is the basis for new proposals to connect networks of smart-devices [10, 11]. While the results presented in this paper are based on these two routing protocols, we believe that any link-based routing scheme will face similar issues when operating in the wireless domain.

The outline of this paper is as follows. In Section 2, we provide a brief survey of wireless routing protocols. In Section 3, we discuss the model and simulation setup that we use to test the various networking schemes. In Section 4, we present the simulation results and discuss their implications.

2. A BRIEF SURVEY OF WIRELESS ROUTING PROTOCOLS

In this section, we provide a brief survey of the various routing schemes that have been developed for wireless multi-hop networking (a larger survey can be found in [14]).

Routing protocols find paths in either a *proactive* or *reactive* fashion. In proactive routing, each user maintains an up-to-date route to every other user, which is achieved by a periodic control messaging throughout the network. This approach is the most similar to wired networks, which typically also use a proactive routing strategy [26, 27]. In reactive routing, a user will "discover" a route to another user only when it has data destined for that user. To find a route, a control packet is flooded across the network that identifies a path towards the destination. Reactive routing is intended to lower network resource utilization by only sending control information when there is data to send, which comes at the cost of higher setup delay [28].

Link-based routing approaches can be further broken down by the type of information that is exchanged: distance-vector, link-state, and geographic. For distance-vector routing, each user maintains a table of its neighbors' perceived distance to any other user in the network. A user then forwards a packet to the neighbor that is the shortest distance from the destination. Examples include Ad-Hoc On-Demand Distance Vector (AODV) routing [23] and Destination-Sequenced Distance Vector (DSDV) routing [29]. In link-state routing, each user disseminates its entire view of the topology to every other participant in the network. With this full network view, each user can then decide the best path to transmit a packet across. Examples include Optimized Link-State Routing (OLSR) [24] and Open Shortest Path First with Manet Designated Routers (OSPF-MDR) [20]. For geographic routing, each user maintains the geographic location of every other user in the network. A packet is then forwarded to the neighboring user that is geographically closest to the destination. Examples include Greedy Perimeter Stateless Routing (GPSR) [30] and Location Aided Routing (LAR) [31].

The basic mechanism of how link-based routing schemes operate is as follows: a user broadcasts a control message (called a "hello") to all of its neighbors. If a series of hello messages are exchanged between two users, a link is considered to exist between them. Routes are then be formed between users using this link information, which is distributed across the network according to the mechanism that is unique to each protocol. When a link has high reliability and does not frequently change, this scheme works well: shortest paths are formed using the available link-state information, and messages can be reliably transported across the links of that route. But when a link is not reliable or changes more frequently, link-state information is less reliable at building stable routes. For changes due to mobility or blockage, wireless routing protocols will try to repair the route by finding a new path. This repair process is typically accomplished on the order of seconds.

To help mitigate the potential issues arising from unreliable links, a number of approaches have been proposed, with the ETX metric [19] being the most well-known of these schemes. A brief description of ETX is as follows. For a given window of time, the number of hello packets that a user receives from a neighbor is counted. A cost is then assigned to the link based on how many hello messages were heard; a link that has fewer hellos successfully transmitted across it will be assigned a higher cost, and hence, will be less likely to be used. ETX continues to be part of new networking standards for low-power devices operating in lossy environments [13].
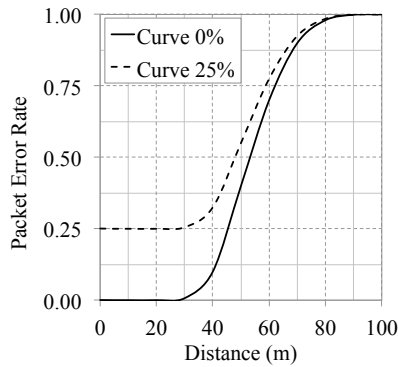
3. MODEL AND SIMULATION SETUP

Figure 1: Packet error rate curves for IEEE 802.15.4 devices [32]

In this section, we present our model and simulation setup. In Section 3.1, we discuss our channel model, and in Section 3.2, we present our simulation environment and the details of our test scenarios.

3.1 Channel Model

When modeling the wireless channel, researchers often use a strict cut-off for transmission distance: any device within a certain distance of the transmitter will receive the message, and any device beyond that distance will not. Even if we assume there are no other active transmitters that can be potentially interfering, this is not a realistic model for a wireless channel: there is no strict cut-off. The effects of multi-path, thermal fluctuations, and other random variations of the environment or atmosphere will induce a "transition region" in which the probability of packet error increases from 0 to 1.

For our wireless channel model, we use the packet error rate (PER) curve for IEEE 802.15.4 devices from [32], which is reproduced as `Curve 0%` in Figure 1. The authors of [32] determined the packet error rates through both simulations and hardware measurements. Other studies have shown similar PER curves [33, 34].

We hypothesize that link-based routing protocols are particularly vulnerable to the effects of the transition region. Control packets will occasionally be successfully exchanged by users that are a far distance apart, which will lead to poor quality links being selected for routes. These long-distance links will typically be preferred over shorter, more reliable links in a shortest path routing protocol. Routes continue to use the long-distance link until the link timeout period expires (which can be up to 6 seconds [24]). To the best of our knowledge, there has been no extensive characterization of wireless routing protocols operating in the presence of a transition region with respect to packet error rates.

`Curve 0%` from Figure 1 assumes no loss for short range transmissions. However, in the presence of interfering wireless devices, one would not error-free communications. Various papers have tried to quantify the effects of interference on packet reception rates for devices
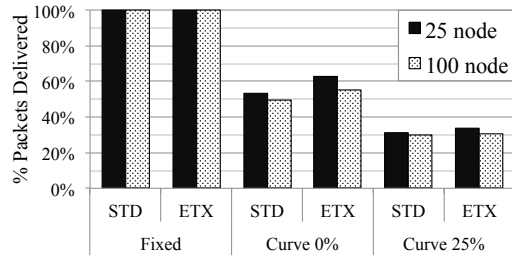
operating in the 2.4 GHz ISM band (where 802.15.4 or 802.11 operates) [32, 35, 36]. These studies find that loss can easily be on the order of 25%, if not greater. With the proliferation of wireless devices operating in the ISM band, this inter-device interference is only going to become more problematic. Hence, it is important that we examine the behavior of link-based routing in the presence of a lossy environment. We define a new curve for a higher loss environment where the minimum PER is 25% for short range transmissions. The PER curve to model interference that causes 25% packet loss is constructed by multiplying the packet success rate at any given distance d (i.e., $(1 - \text{PER}(d))$) from `Curve 0%` by $(1 - 0.25)$. We label this curve `Curve 25%`, which is also shown in Figure 1.

Additionally, we compare the effect of the transition region with the more traditional transmission model often used in literature that assumes a user has a fixed transmission range, where within that range all transmissions are successful. This fixed-distance error curve has the following parameters: a transmission under 40 meters has 0% PER (100% reception), and a transmission over 40 meters has 100% PER. We label the curve with a fixed transmission distance as `Fixed`.
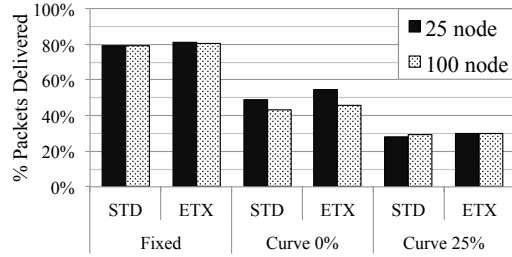
3.2 Simulation and Scenario Setup

Of the wireless routing protocols discussed in Section 2, we evaluate Ad-hoc On-Demand Distance Vector (AODV) routing and Optimized Link State Routing (OLSR). AODV is a reactive distance vector protocol, and it forms the basis of many of the newest wireless networking proposals [10]. OLSR is a proactive link-state protocol, and is considered to be one of the the more mature wireless routing protocols [28]. For both OLSR and AODV, we operate them in "standard" mode, which is the routing protocol with its default parameters, and in "ETX" mode, which has ETX metrics enabled.

The parameters of the simulation are as follow. Our network consists users randomly distributed within a circular region of two different sizes. First, we wish to examine the effect of density on the network: the first circular region has a radius of 100 meters, and we test a network of 25 and 100 users. Next, we wish to examine the effect of diameter (longest path) of the network: the second circular region has a radius of 150 meters, and we only test a network of 100 users (a 25 node network would not be able to be connected in such a large area). The test is run for a total of 30 minutes (1800 seconds) of simulation time. For both OLSR and AODV, we test two variants: standard (STD) and ETX. For mobility, we test two cases: a completely static network and a mobile network. In particular, for the case with mobility, we use a random waypoint model, where users choose a speed uniformly between 0 and 3 m/s with zero hold-time. In order to avoid the effects of conges-

Figure 2: AODV 100 meter radius: Packet delivery success rate

Figure 3: OLSR 100 meter radius: Packet delivery success rate

tion and queue overflows, data rates are set arbitrarily high. All of our simulations are performed using the OPNET newtork modeler [37], which has AODV and OLSR implemented according to IETF specifications.
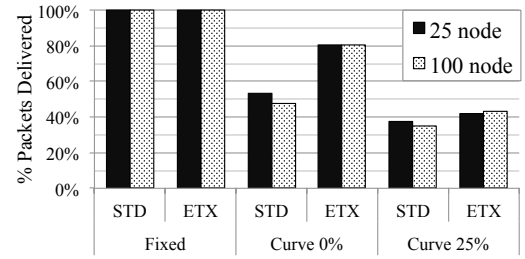
4. SIMULATION RESULTS

In this section, we present and discuss the simulation results for routing in wireless networks. In particular, we demonstrate that link-based routing (1) experiences high packet loss due to the inherently unreliable nature of control information in the presence of the transition region, (2) is unable to ensure reliable message delivery in the presence of a lossy environment, and (3) incurs a high cost for route maintenance and repair. To assess the performance of link-based routing schemes, we measure both the packet delivery rate and the amount of overhead generated by the routing protocols.
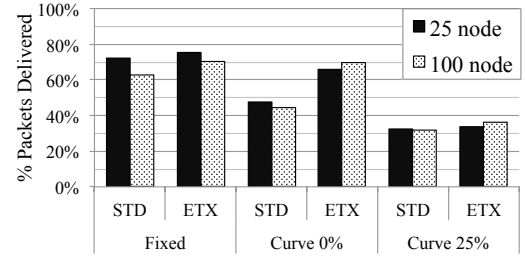
4.1 Packet Delivery Rate

We begin by analyzing the effects that the transition region has on the performance of the routing schemes. We first consider a wireless environment with no errors along short range links, which is given by the packet error rate curve `Curve 0%`. Without mobility, the only cause of packet loss in this scenario is from the routing protocols choosing poor quality links that are of longer distance over high quality links that are shorter in length. To see the effect that poor-quality link information has on packet delivery rates, we plot the percentage of packets that were successfully received at the destination for AODV and OLSR in Figures 2 and 3, respectively.

For AODV, in the best case scenario of no mobility and no interference (given by `Curve 0%` in Fig. 2a),
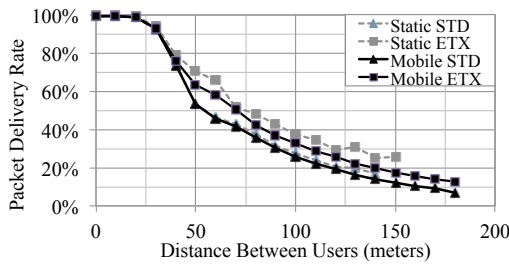
only 52% of packets are delivered for the standard mode in the 25 node network. For the 100 node network, 49% of packets are delivered in standard mode. When no transition region is present, as is modeled by the `Fixed` curve, packets are received 100% of the time without mobility. Due strictly to the presence of the transition region, about half of the packets are lost. With the transition region, control packets are occasionally exchanged across poor-quality long-distance links, and these links are then preferred for shortest path routes. The results suggest that use of a fixed transmission range in modeling wireless networks may have given a false impression on the efficacy of varying wireless routing protocols.
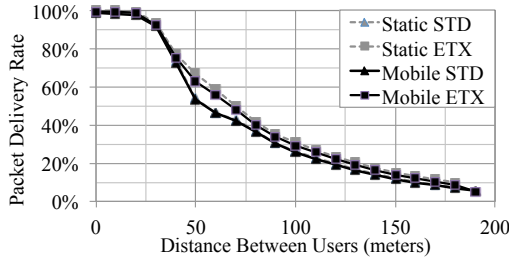
For AODV, enabling ETX only improves delivery rates to 62% for the 25 node network under `Curve 0%`, and 57% for the 100 node network. In AODV, the larger network has a slightly lower packet delivery rate than the smaller network. The reason for this is that in a larger network there is a higher likelihood that a series of control messages being exchanged with a distant neighbor, and that longer link will be preferred for shortest paths. This poses a problem as networks scale in size: more users leads to a greater chance of establishing a poor quality link. Once this link is established, it is continued to be used for paths until some time-out period expires.

When we move to the more realistic lossy environment where we model packet loss on short-range links (as given by `Curve 25%`), delivery rates drop even further. AODV is only able to deliver approximately 30% of all packets transmitted. ETX does not provide much benefit for delivery rates in this lossy environment.

We next look at the performance of OLSR. We observe that the standard mode performs worse than its
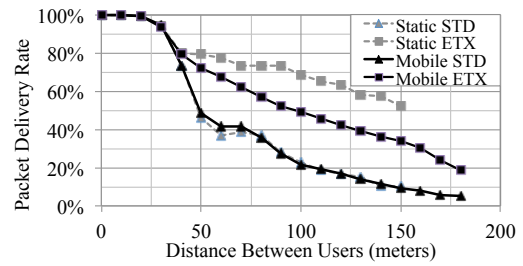
(a) 25 node network

(b) 100 node network

Figure 4: AODV 100 meter radius: Packet delivery rate for `Curve 0%` based on distance between users

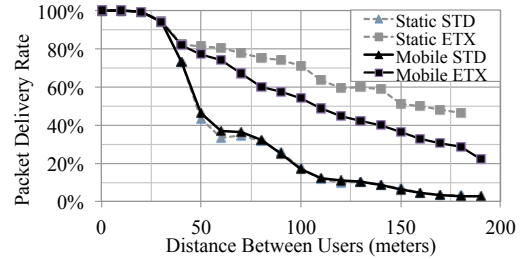**(a)** 25 node network

(b) 100 node network

Figure 5: OLSR 100 meter radius: Packet delivery rate for `Curve 0%` based on distance between users

AODV counterpart, but OLSR ETX performs better than AODV ETX. With `Curve 0%`, OLSR standard only successfully delivers 50% of packets in the 25 node network, and 45% of packets in the 100 node network. OLSR ETX is able to bring delivery rates up to 80% in the case of static network, and up to 70% for the mobile one. The reason ETX performs better for OLSR than it does for AODV is because OLSR is a proactive routing protocol that is constantly exchanging control messages. With this constant flow of control data, OLSR is better able to measure the packet success rate over a link, which allows it to better assign weights to those links. As we will show, the improvement that ETX provides comes at the expense of significantly higher control messaging in OLSR, which may be problematic in a resource-limited wireless environment. When interference is modeled, and links are no longer error-free, ETX no longer provides the same benefit. Under `Curve 25%`, the packet delivery rate drops in the static case drops to 35% for standard mode and 42% for ETX. With mobility, the packet delivery rate is 31% for standard and 38% for ETX.

The results shown in Figures 2 and 3 are the overall packet delivery rates for a network with a 100 meter radius. This includes data that travels between users that are 15 meters apart and users that are 150 meters apart. For the all-to-all traffic that is modeled, a large proportion of users are within a single-hop of their destination. In our tests, 30% of users are less than 50 meters apart from one another; these users will typically not form multi-hop paths. The packet delivery rate for users that are less than 50 meters apart exceeds 90% for all cases tested when using `Curve 0%`. For the other
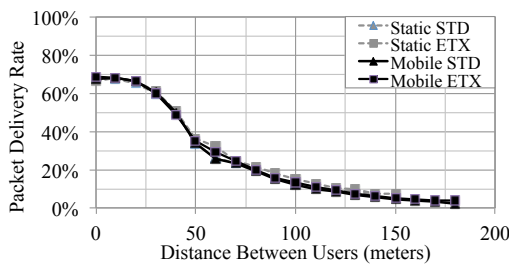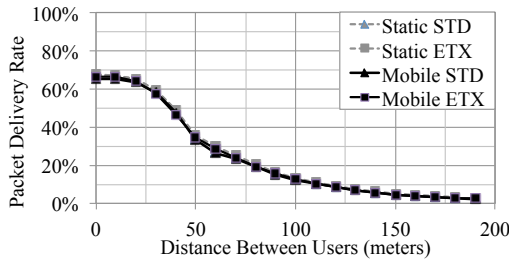
70% of node pairs, multi-hop paths are necessary to connect users, and the error rates significantly increase as poor-quality long-distance links are selected for paths.

In Figures 4 and 5, packet delivery rates are shown as a function of distance between users for `Curve 0%` in a network with a 100 meter radius. We note that the distance between users is not necessarily the path length; users that are 60 meters apart may connect through a user that is 40 meters away from each of them, which results in a path length of 80 meters. Hence, the distance between users gives a lower bound on the total path length connecting any two nodes.

We first observe that all users that are less than 30 meters apart from one another have close to 100% packet delivery success. The direct, reliable link is almost always selected to transmit data between these users. Starting at approximately 40 meters, the packet delivery rate sees a sharp decline. This is especially noticeable for the standard mode for both AODV and OLSR. For `Curve %0`, the link error rate goes from 10% to 70% between 40 and 60 meters. Given a successful exchange of control packets, a link will be considered established. Users that are 60 meters apart from one another will typically use the 60 meter link if they believe it exists. The routing protocol will believe the poor-quality link exists until no set of control packets are exchanged for the length of a timeout period, which is typically a cycle of 2 or 3 hello messages. Users that are farther apart will have more opportunities to select a long-distance poor-quality link. In this network, 30% of all users are more than 100 meters apart, and these users only have 30% of packets successfully delivered. Users that are 150 meters apart only see a 15% delivery

(a) 25 node network

(b) 100 node network

Figure 6: AODV 100 meter radius: Packet delivery rate for `Curve 25%` based on distance between users

(a) 25 node network

(b) 100 node network

Figure 7: OLSR 100 meter radius: Packet delivery rate for `Curve 25%` based on distance between users
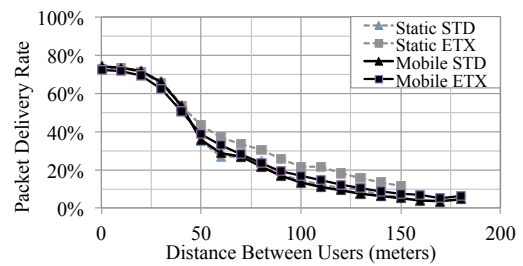
rate.

The use of ETX does not significantly improve performance for AODV. For OLSR, ETX does offer benefits, but its efficacy diminishes with increased distance between users, as well as with mobility. With mobility, OLSR ETX can delivers only 50% of packets for users that are 100 meters apart, and the longest distance users (180 meters apart) have packet delivery rates of 20%.
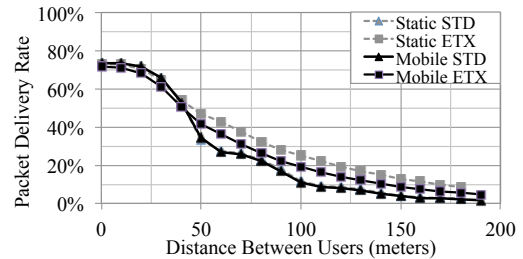
Again, with `Curve 0%`, shorter links are error-free. For the static case, the packet loss shown in Figures 4 and 5 are due to the routing protocols selecting poor quality links for the paths. In contrast, when transmissions are modeled as a fixed distance without a transition region, the routing protocols are able to deliver 100% of the packets without mobility.

For the more realistic lossy channel model (using `Curve 25%`), Figures 6 and 7 show the packet delivery for AODV and OLSR, respectively, as a function of distance between users. Packet delivery rates for users that are multiple hops apart from one another see a significant drop. For AODV, users that are 100 meters apart only expect to have 10 to 15% of packets delivered. Users that are 150 meters apart only have approximately 5% delivery. For AODV, ETX provides no benefit in the modeled lossy environment.

In the non-lossy environment previously modeled, OLSR ETX performed significantly better than standard OLSR. In the lossy environment, the benefits of ETX have greatly diminished. For users that are 100 meters apart, OLSR ETX only successfully delivers 30% of packets. This is still an improvement over standard OLSR, which delivers less than 15%, but it is not nearly as beneficial as it was when short-range links were error free. When users are 150 meters apart, OLSR ETX can only suc-

cessfully deliver 15% of of packets, and standard OLSR delivers less than 5%.

A large source of the low delivery rate for multi-hop connections is the effect of compounding errors: a three-hop path has three opportunities for a packet to be lost. If each link has a PER of 25%, then there is only a 58% chance that a packet will be successfully delivered. With the addition of having a transition region for packet error rates, there may be significantly higher packet loss due to the routing scheme choosing poor quality links to form paths. These effects together lead to link-based routing schemes not being able to reliably deliver data in a lossy environment.

If we increase the area that the users are spread across, then the length of the longest path (also known as the network diameter) increases. In Figure 8, we show the packet delivery rate for a 100 node network distributed across the larger circular region that has a radius of 150 meters. In particular, we highlight the difference in delivery rate between a network distributed in a circular region with a radius of 100 meters and a region with a radius of 150 meters by comparing the two side-by-side. Since the larger network is sparser, mobility may induce packet loss due to users being isolated; hence, we do not show packet delivery results for the mobile case. With users distributed over a larger area, 85% of user-pairs are more than 50 meters apart, as opposed to only 70% in the smaller area network. Because of this larger distance, this allows routes to have more opportunity to select poor quality long-range links, hence bringing down the overall packet delivery rate. Under `Curve 0%`, both AODV and OLSR see a delivery rate that is significantly lower for the larger area network. In standard mode, AODV goes from 50% delivery rate to
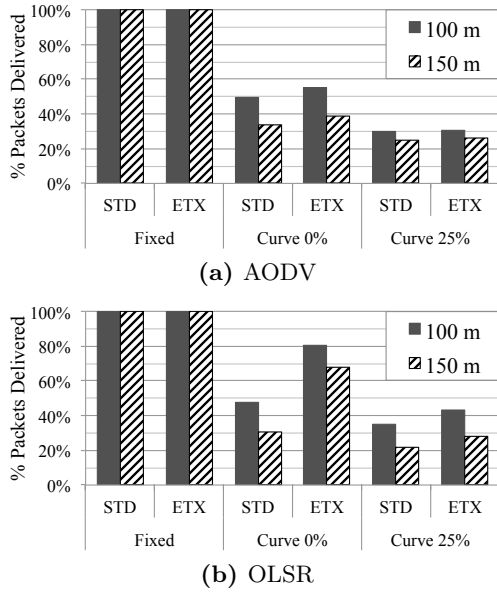
(a) AODV

(b) OLSR

Figure 8: 100 and 150 meter radius with no mobility: Packet delivery success rate

(a) `Curve 0%`

(b) `Curve 25%`

Figure 9: 100 and 150 meter radius with no mobility: Packet delivery rate based on distance between users

a 33% delivery rate, and OLSR goes from 48% delivery to 30%. A similar drop in delivery rate is seen for the larger network when ETX is enabled, as well as when a lossy environment is modeled via `Curve 25%`.

We next look at the packet delivery rate for AODV and OLSR as a function of distance between users for a network with a radius of 150 meters for both `Curve 0%` and `Curve 25%`, shown in Figure 9. In this larger area network, 51% of users are over 100 meters apart from one another, and 21% are over 150 meters apart. For `Curve 0%`, AODV standard and ETX deliver only 20% of packets for users that 100 meters apart, and only 10% for users that are 150 meters apart. This is a similar value for standard OLSR. OLSR with ETX performs better, delivering 68% of packets for users 100 meters apart, and 51% of packets for users 150 meters apart. When a lossy wireless channel is modeled using `Curve 25%`, all variants perform significantly worse, and OLSR with ETX again no longer provides the same benefits. For users 100 meters apart, only 10% to 20% of packets are delivered, and for users 150 meters apart, between 5% and 12% of packets are successful.

4.2 Routing Overhead

Next, we examine the amount of network resources used to find and maintain routes between users. Wireless networks have lower capacity than their wired counterparts, and hence, and routing scheme should occupy as little bandwidth as possible to setup and maintain paths. Additionally, many new wireless devices will be power constrained, and high levels of control messaging can potentially waste critical battery resources. High levels of control traffic may cause an increase in interference, which further degrades the channel and overall network performance. Due to space constraints, we only
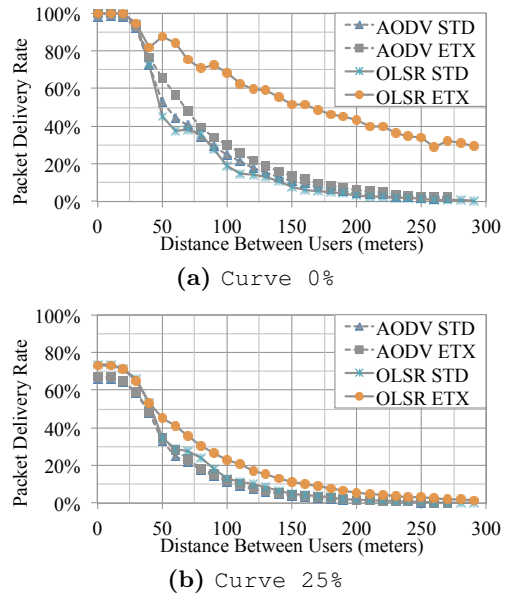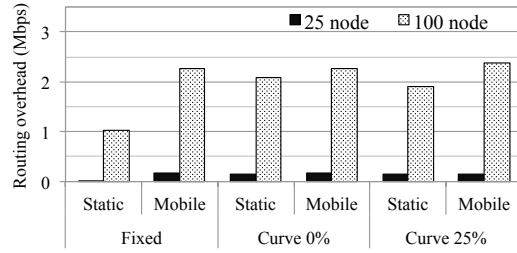
show the results for the network with a radius of 100 meters; the 100 node network generates similar routing overhead for both the 100 meter and 150 meter network. Figures 10 and 11 show results for overhead generated by AODV and OLSR, respectively.
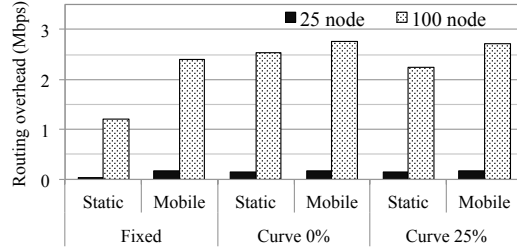
The most noticeable observation is the dramatic increase in network resource utilization when going from a 25 node network to one with 100 nodes. For standard mode, AODV uses between 14 and 170 kbps for the 25 node network, and between 1.9 and 2.7 Mbps for the 100 node network. OLSR STD uses approximately 50 kbps for the 25 node network, and 1.3 Mbps for the 100 node network. This is an increase of up to 70x for AODV and 26x for OLSR. A similar increase is seen when ETX is enabled.

Unfortunately, the resources available to the network do not scale similarly. Users in a wireless network contend for the same wireless resources; hence, the overall capacity available to a group of users does not scale proportionally as the number of users in the networks grows. This fundamental result was demonstrated in [38], which shows that as the number of users in the network grows to infinity, the resources available to each goes to zero. For a wireless network protocol to scale well, it needs to grow sub-linearly with respect to the number of users in the network. This is challenging for link-based routing. Hello messages generate significant overhead, with each user sending a hello message for other users to know that it exists and can be used as a next-hop waypoint. A hello message often contains a list of a user's neighbors; in larger networks, users typically have more neighbors, and hello messages can grow significantly in size.

We next discuss two other key observations: (1) OLSR ETX has a large increase in routing overhead over OLSR

(a) AODV Standard

(b) AODV ETX

Figure 10: AODV: Overhead generated
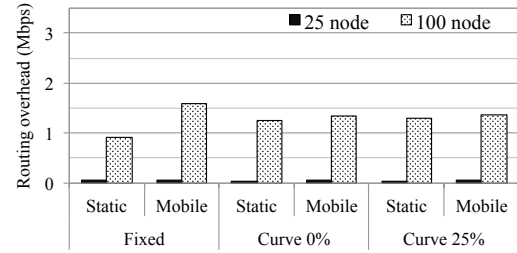

(a) OLSR Standard

(b) OLSR ETX

Figure 11: OLSR: Overhead generated

standard, and (2) AODV in a static network with a fixed transmission radius has significantly lower overhead than any of its counterparts.
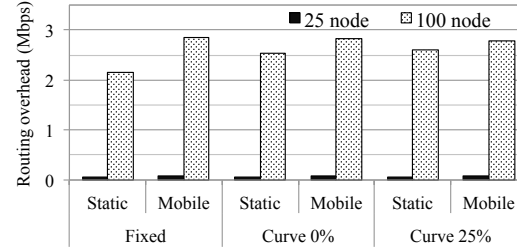
For OLSR, the 25 node used approximately 50 kbps for standard mode, and between 65 and 85 kbps for ETX. In the 100 node network, we see that there exists a factor of two difference between standard mode and ETX; standard mode uses approximately 1.3 Mbps of network resources, while ETX uses 2.7 Mbps. Of the two routing protocols, OLSR showed the largest benefit from the use of ETX, but it comes at the cost of a significant increase in control overhead. When packet loss was introduced to the network (using `Curve 25%`), ETX lost most of its benefit in helping select higher quality routes, but this did not come with a commensurate drop in resource utilization.

For AODV, the 25 node network with no mobility and a fixed transmission distance generates 14 kbps of overhead for standard and 28 kbps for ETX. When a transition region is utilized (`Curve 0%`), control traffic increases to approximately 170 kbps. This is the case for with or without mobility. This is because AODV uses control messaging to try to fix routes that it believes are broken. When the transition region is added, AODV believes it needs to constantly repair paths. In the static case, no users changed location, but now the control traffic generated by AODV matches that of the case with mobility. A network operator may believe that AODV will not generate significant traffic if the users are stationary, but our results indicate that this is not the case.

Having a constant stream of control traffic that is over 2 Mbps or greater can potentially be overwhelming for networks of low-power smart-devices. Proposals

for these future networks anticipate devices being capable of only supporting data rates of 100 kbps [9], with networks scaling to hundreds or thousands of nodes [22]. As networks of low data-rate devices grow larger, scalability will be paramount. In addition to not being able to operate reliably in a lossy environment, link-based routing schemes do not appear to scale well.

5. CONCLUSION

In this paper, we considered how effective routing is for reliably and efficiently delivering data in wireless multi-hop networks. As demonstrated, when short range links are error-free and long-range links have an error-rate proportional to their length (the transition region), control messages will be occasionally exchanged between long distance neighbors. Routing protocols that rely on selecting links to form paths will invariably select low quality connections, leading to significant packet loss.

When packet loss is introduced, link-based routing schemes are no longer able to reliably deliver data. Control information cannot be reliably exchanged, which negates the positive effect that ETX may have had for improving route selection. The amount of overhead that is generated to find links for paths is high in comparison to the quality of the routes that are ultimately selected.

Considering that new proposals for wireless networking continue to be link and routing based, we must consider whether or not this approach is will ultimately pay dividends. The goal of any networking scheme is to reliably deliver data using as few network resources as possible. Link-based routing seems to have inherent flaws that do not make it a good choice for connecting users in a wireless environment, especially as these

networks grow large. A number of novel techniques for data-dissemination are being considered, such as efficient flooding [39, 40] or opportunistic routing [41]. Whether it be one of these approaches, or something else, alternatives to link-based routing need to be pursued if we wish to succeed at connecting the future Internet of Things.

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